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EFFECT OF BLADE TIP SHAPE ON ROTOR DYNAMICS AND AEROELASTIC RESPONSE

by

Jing G. Yen

Bell Helicopter Textron, Inc.

Fort Worth, Texas U. S. A.

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Abstract

Effects of a swept/tapered tip planform on blade weight, dynamic tuning, elastic twist, loads/vibration, and aerodynamic performance are compared with those of a rectangular tip on a four-bladed bearingless rotor using a comprehensive analysis. Validation of the analysis of swept/tapered blade tips is conducted using wind tunnel data. The swept/tapered tip blade has a thrust-weighted chord identical with that of the rectangular planform and is dynamically tuned to match the flapping inertia and rotor dynamics of the rectangular tip blade. Results indicate that, in high-speed flight, the swept/tapered tip reduces pitch-link loads, blade beam bending, and 4/rev hub moments but has insignificant effects on blade chord bending and aerodynamic performance.

To achieve the desired rotor dynamic tuning, a blade weight penalty of 5.4% is identified with the swept/tapered tip. Effects of rotor solidity, airfoil thickness, tip speed, and blade torsional stiffness on the performance of a swept/tapered tip are also discussed.

Notation

Alpha = rotor shaft angle, negative forward, deg.
C_L = lift coefficient, $L/\rho(\pi R^2)(\Omega R)^2$
C_P = power coefficient, $P/\rho(\pi R^2)(\Omega R)^3$
C_x = rotor propulsive force coefficient, $D/\rho(\pi R^2)(\Omega R)^2$
D = rotor drag force, lb
L = rotor life force, lb
$M_{1,90}$ = advancing tip Mach number
P = rotor shaft horsepower x 550, lb-ft/sec
R = rotor radius, ft
μ = advance ratio
ρ = air density, slug/ft^3
σ = rotor solidity
Ω = rotor speed, rad/sec

Introduction

Reducing helicopter oscillatory loads while improving performance and reducing noise through passive control has long been the design goal for helicopter engineers. In the late seventies and early eighties, significant efforts by the U. S. Government and the industry were made on the Aeroelastically Conformable Rotor (ACR). The concept of the ACR was to incorporate tip sweep, taper, and anhedral with torsionally soft blades (Refs. 1–3) to improve performance and reduce loads. Based on the data reported, the authors found that the ACR applications for the tip shapes tested resulted in higher loads and poorer performance than for the baseline rotor, that there did not exist a strong correlation of magnitude of advancing blade elastic twist with rotor performance and flapwise loads, and that the configurations which produced small azimuthal activity in elastic twist were the best performers.

Extensive research has been conducted in recent years to further quantify the benefit of various tip shapes. Analytical studies of the effect of sweep on hub loads (Ref. 4) and aeroelastic stability (Ref. 5) revealed that sweep was not beneficial for all rotor blades, that no optimal sweep angle was found for aeroelastic stability or loads at all speeds, and that the tip shape, as a design parameter, should be included in the early stages of a rotor design process.

Wind tunnel tests of a model rotor were conducted (Ref. 6) to determine the effects on dynamic response and aerodynamic performance by varying the tip design of the outboard 8% radius. Four different blade tip geometries or shapes having different planform, sweep, taper, and anhedral were tested. Results from the tests showed that blade torsional moments and control system forces were reduced by adding sweep or anhedral. The anhedral tip benefited hover performance while the swept/tapered tip provided the best performance at high advance ratios.

Another wind tunnel test was conducted to measure the aerodynamic benefit of a parabolic swept-back tip with anhedral on a 3-bladed model rotor equipped with very rigid blades (Ref. 7). The sweep onset was at 90% radius. Significant improvements on hover and forward flight performance and noise reduction over a rectangular planform were achieved. However, the test was aerodynamically motivated with no consideration for aeroelastic optimization.

A test of a full-scale rotor was conducted in the NASA Ames 40- by 80-foot wind tunnel to investigate performance, acoustics, and loads of a rotor with various tip planforms (Ref. 8). The four tips (rectangular, tapered, swept rectangular, and swept/tapered) were interchangeable over the outer 4.5% radius. Data showed that the planform taper had the largest impact on the overall performance while sweep effects were secondary and only showed up at the higher advance ratios, and then only for the swept rectangular configuration. At advance ratios of 0.2 to 0.3, there was a 4% reduction in profile power which was a direct result of the reduction in blade area near the tip. Both tip taper and tip sweep improved the acoustic signature. At 0.38 advance ratio and 0.9 tip Mach number, major reductions in oscillatory pitch-link loads were demonstrated for the swept/tapered configuration.

Results of a flight test of a swept-back parabolic tip on a Dauphin-365N were reported in Ref. 9. Additional weights were added at 45% radius for the dynamic tuning of the second lead-lag mode. The tip planform improved hover (2%) and forward flight (1 to 6%) performance and reduced perceived noise level (1.25 EPN dB). The swept-back tip, however, also resulted in high steady and 1/rev pitch-link loads and large blade torsional deformations.

Another version of the swept-tapered/anhedral blade tip design was flown on the AS332 Super Puma MK II (Ref. 10). The onset of the sweep/taper was at 96% radius. While improvement in hover (1%) and forward flight (5 kn at sea level ISA) performance was realized, high 3/rev blade flapping moments were also reported. Hence, a 50% increase in cabin vibrations was measured. The cabin vibration level was reduced by employing blade pendulum absorbers.

The Westland Lynx helicopter set a world speed record at 216.3 kn in August 1986 (Ref. 11) with the BERP main rotor. It was stated that in addition to judicious selection of spanwise distribution of airfoils for forward flight performance and balance of blade pitching moments, care was also exercised in the dynamic tuning of the BERP blade (Ref. 12). Flight test data (Ref. 12) indicated that, with respect to the standard metal blade, the fuselage vibration at high speed was benefited by the BERP blade, but the control loads were nearly doubled at all speeds.

From the above literature survey, the following observations are made:

1. Most of the research on the effect of tip shape on performance and dynamic response has focused on aerodynamics. This was evidenced by employing interchangeable tips on very rigid blades. Furthermore, the potential weight penalty of using a non-rectangular planform was not addressed.

2. The benefit of sweep, taper, and anhedral on aerodynamic performance and acoustics was relatively well understood and documented. The effect of tip shape on loads, vibration, and aeroelastic response, however, was inconclusive.

The effect of blade tip shape on rotor dynamics and aeroelastic response has not been well documented. Blade design parameters, such as thrust-weighted chord, airfoils, twist, rotational inertia, weight constraint, cg–aerodynamic center–elastic axis relationship, dynamic tuning, and torsional stiffness, may drastically influence the performance of tip shape on loads, vibration, and aeroelastic response. Tip shape selection should, therefore, be treated as an integral part of the rotor design process.

This paper will discuss the effect of a swept/tapered tip planform on loads, vibration, aeroelastic response, and forward flight performance on a generic but realistic 4-bladed bearingless rotor. Results of the swept/tapered tip are compared with those of a rectangular tip. Both rotors have identical thrust-weighted solidity. The impact on cost, weight, and dynamic tuning of the swept/tapered tip in comparison with the rectangular planform is discussed and identified. Blade design parameters such as rotor solidity, airfoil thickness, and blade torsional stiffness, which may influence the performance of the tip planform on blade dynamic response, will be briefly addressed. The advantages of treating the tip shape as a design parameter in the early stages of a rotor design as opposed to the "interchangeable tip approach" will be assessed and emphasized.

Validation of Methodology

The analysis used in this paper is COPTER (Ref. 13). In COPTER the tip is modeled in the following fashion. The load points are defined at the quarter chord for each blade segment. The sweep is input to the program by specifying the offsets of the quarter chord from a straight reference axis, which is usually coincident with the pitch change axis. COPTER uses these offsets to compute the appropriate velocity components at each blade segment. The geometric pitch of the segments is also redefined to account for the kinematics of the swept tip. The blade taper is represented by inputing the appropriate chord length at each blade segment. A state-of-the-art dual-circulation free wake model by Johnson (Ref. 14) is used. The wake is modeled using a second order swept lifting line theory with a vortex core radius of 0.015R.

To validate the tip methodology, correlation was conducted using performance and loads data from a wind tunnel test on a full-scale articulated rotor with four interchangeable tip planforms. The experimental data were reported in Ref. 15. The four tip planforms—swept/tapered, swept, tapered, and rectangular—are shown in Fig. 1 (copied from Fig. 6 in Ref. 15). The structural and aerodynamic properties needed to model the rotor and each of the four different tip configurations were obtained from Ref. 16. The blade employed a $-10°$ linear twist and 9.5% tip airfoil thickness. Correlation of computed rotor natural frequencies with the whirl test data (Ref. 16) is shown in Fig. 2. Correlation is good except for the frequency of the torsion mode. The level of correlation in the torsion mode, however, is as good as that reported in Ref. 16.

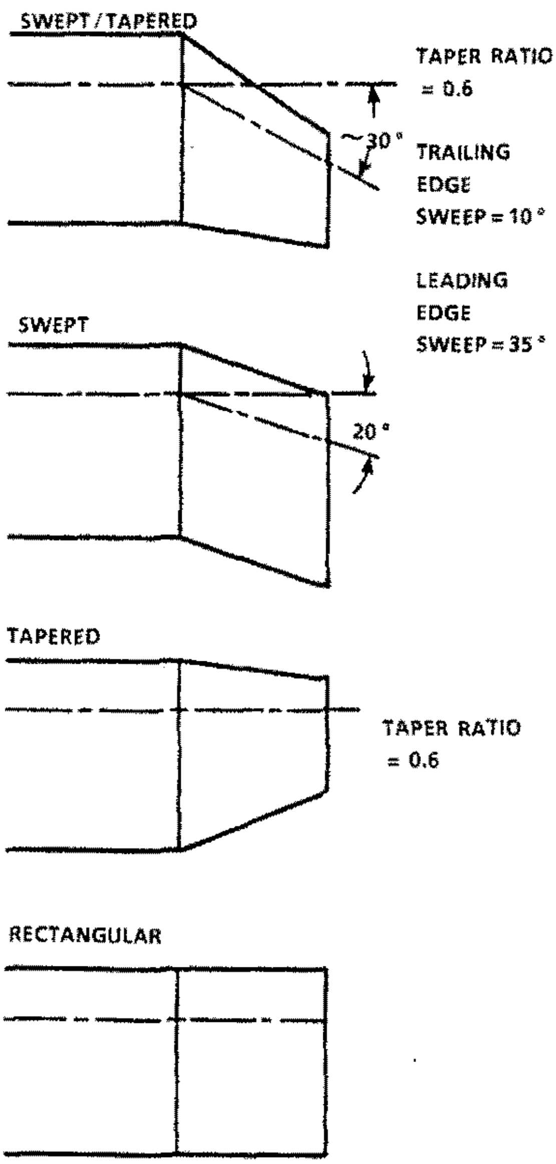

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Fig. 1. Tip planform geometry.

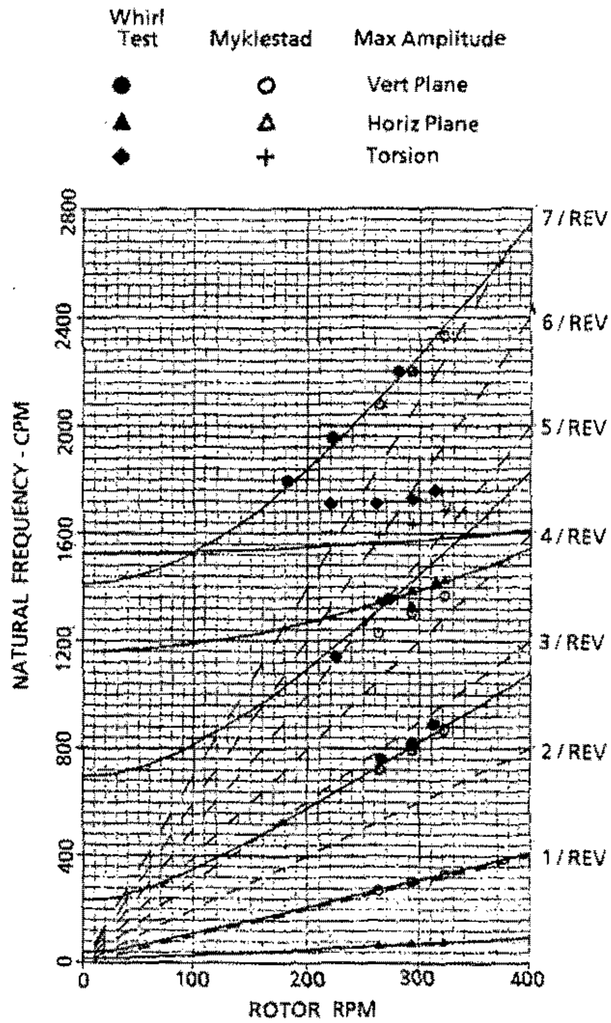

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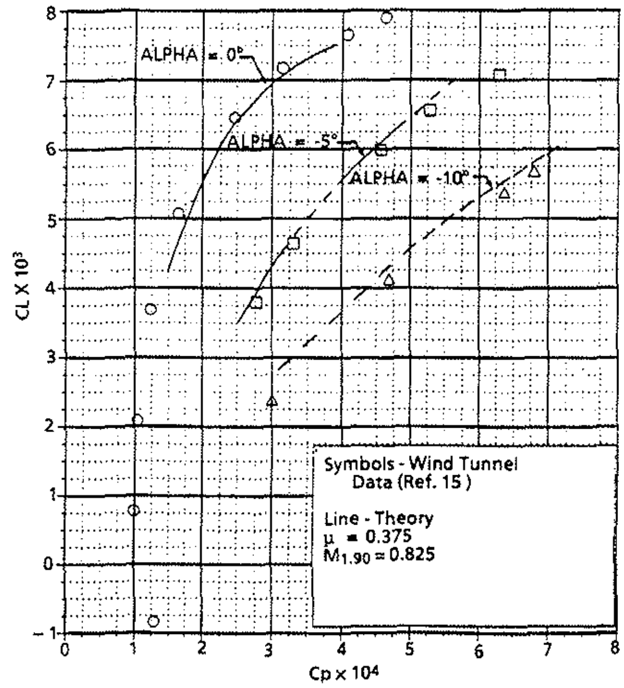
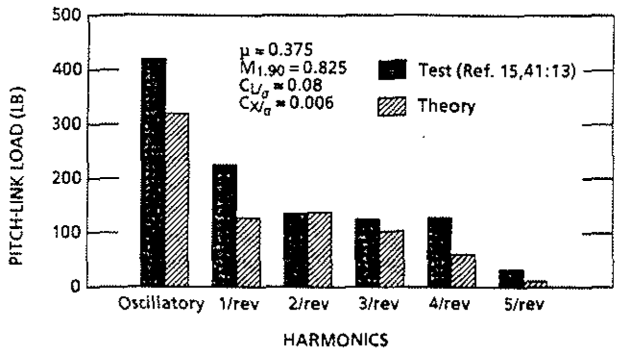
Fig. 2. Rotor natural frequencies, a full-scale articulated rotor with swept/tapered tip.

Performance correlation with the rectangular-tip blade is shown in Fig. 3 at three different shaft angles, 0°, $-5°$, and $-10°$. The wind tunnel simulation was conducted at 150 kn, 293 rpm. Similar correlation (not shown) was achieved with the swept/tapered tip blade. The level of correlation substantiated the COPTER aerodynamic capability.

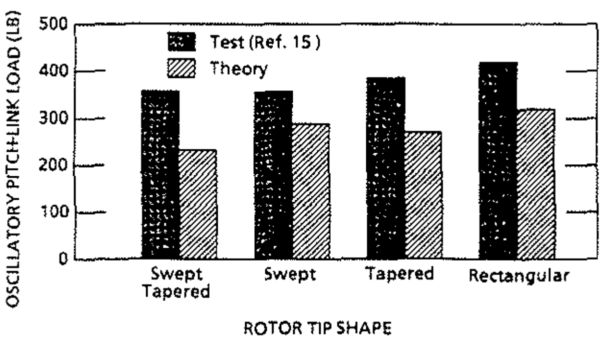
Correlations of pitch-link loads are depicted in Figs. 4–6. Data in Fig. 4 represent harmonic decompositions of pitch-link loads at 150 kn for the rectangular tip. The correlation is good except for the 1/rev. The lower prediction of the 1/rev component resulted in lower prediction of the overall oscillatory. The lack of correlation in 1/rev could be attributed to the lack of definition of the blade feathering bearing springrate which was not provided in Ref. 16. For this correlation, the feathering springrate was estimated as 143 in-lb/deg and was provided to Bell by NASA Ames. Data in Fig. 5 show correlations of the oscillatory pitch-link loads of the four tip planforms.



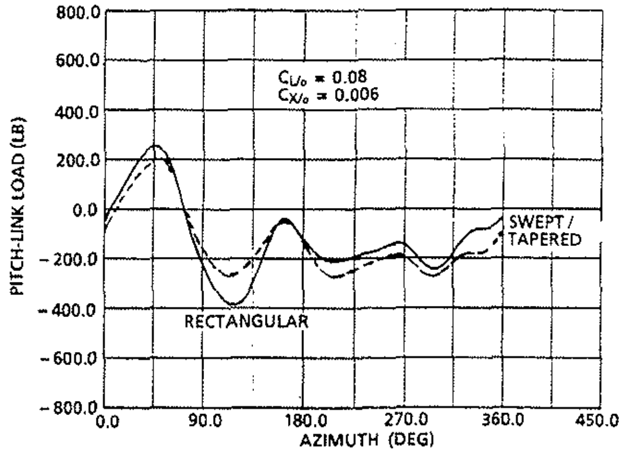
3H915
Fig. 3. Performance correlation of a full-scale articulated rotor with rectangular-tip blade.



3H917
Fig. 4. Harmonic decomposition of pitch-link loads of a full-scale articulated rotor, rectangular tip.



3H919
Fig. 5 Pitch-link loads correlation of a full-scale articulated rotor, $\mu = 0.375$, M1,90 = 0.825, CX/σ = 0.006, CL/σ = 0.080.



3H916
Fig. 6. Computed pitch-link load waveforms of a full-scale articulated rotor, $\mu = 0.375$, M1,90 = 0.825

Correlation of the pitch-link loads in trend with the four tip shapes is demonstrated. The reason for the reduction in pitch-link loads for the swept-tapered tip over the rectangular tip shown in Fig. 5 was investigated by reviewing time history waveforms. The computed waveforms are shown in Fig. 6. Results indicate that compressibility relief with the swept/tapered planform reduced the pitch-link load on the advancing blade. A close examination of the analytical data revealed that a reduction of Mach number from 0.825 to 0.77 and a reduction of nose-down elastic twist by 0.5° due to the tip sweep were responsible for the reduction in loads.

Impact of Swept/Tapered Tip Planform on Loads, Vibration, Aeroelastic Response and High Speed Performance

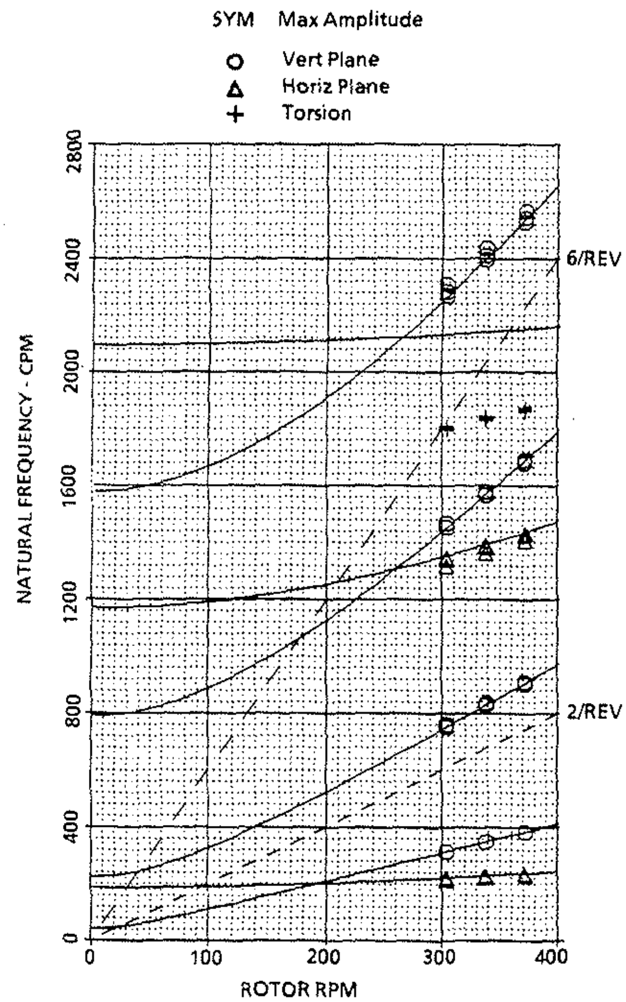
To evaluate the potential benefit of tip shapes, data from several sources were studied. Of these, the swept/tapered tip tested at NASA Ames 40- by 80-ft wind tunnel (Ref. 15) showed promise for performance improvement and reduction in loads. For study purposes, the geometry of this swept/tapered tip planform was used in this paper.

Baseline Rotor, Rectangular Tip, $\sigma = 0.0715$

A generic yet realistic and well-tuned 4-bladed bearingless rotor with rectangular tip was selected as the baseline. The rotor was sized for a design gross weight of 8400 lb and a flat plate drag area of 14.1 ft². Blade airfoils were optimized for aerodynamic performance. Thickness taper was from 12% at 0.65R to 6% at the tip. the thrust-weighted solidity of the baseline rotor was 0.0715. Other prominent rotor characteristics for the rectangular tip (baseline) blade are given in Table 1. The fan plot of the baseline rotor is shown in Fig. 7.

Table 1. Rotor Characteristics of a Bearingless Rotor with Rectangular and Swept/Tapered Tips

	Units	Rectangular	Swept/ Tapered
Number of blades	–	4	4
Radius	ft	21	21
Tip speed	ft/sec	743	743
Twist	deg	-12	-12
Thrust-weighted solidity	–	0.0715	0.0715
Blade weight	lb	87	91.7
Flapping inertia/ blade	slug-ft^2	471	472



3H948

Fig. 7. Computed rotor frequencies of a bearingless rotor, rectangular tip.

Swept/Tapered Tip, σ = 0.0715

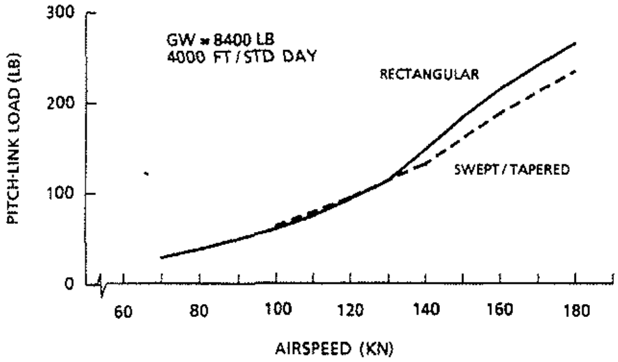
Rotor Tuning. To isolate the effects of the swept/tapered (S/T) planform on loads and high-speed performance, the blade chord of the S/T tip was increased to match the thrust-weighted solidity of the baseline rectangular blade. The S/T blade was also tuned to closely match the frequencies of the baseline rectangular blade. Rotor characteristics and natural frequencies of the S/T blade were compared with those of the rectangular tip blade. The results are shown in Table 1 and Table 2. Note that the weight of the S/T blade was 4.7 lb heavier than that of the baseline blade because the S/T tip geometry did not allow the positioning of the spanwise tuning weight at the extreme tip. As a result, a 5.4% weight penalty was assessed.

Table 2. Comparison of Rotor Natural Frequencies of a Bearingless Rotor

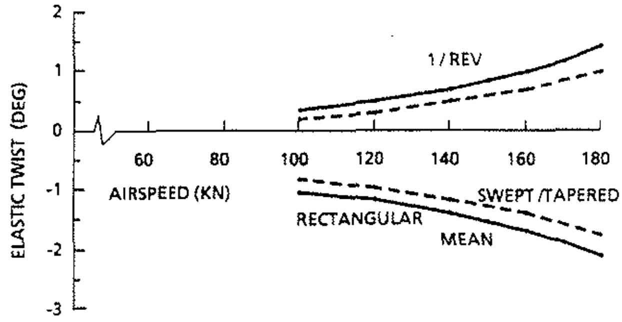
Natural frequencies (/rev)	Rectangular	Swept/ Tapered
1st inplane mode	0.67	0.68
1st out-of-plane mode	1.03	1.03
2nd out-of-plane mode	2.46	2.46
2nd inplane mode	4.09	4.22
3rd out-of-plane mode	4.63	4.65
Torsion	5.45	5.20

Pitch-Link Loads. Variations of oscillatory pitch-link loads with airspeed for the rectangular and S/T blades are shown in Fig. 8. Clearly, the benefit of the S/T tip on pitch-link load reduction was not realized below 130 kn. At 180 kn, a 10% reduction was predicted. Time histories of the pitch-link loads at 180 kn are compared in Fig. 9. The reduction in peak tension loads took place on the advancing blade near 110° azimuth position. Since the bearingless rotor had a trailing edge pitch-horn, the reduction apparently was caused by a decrease in nose-down blade pitching moment or elastic twist. Harmonic decomposition of the pitch-link loads at 180 kn is shown in Fig. 10. The reduction in the overall oscillatory loads was largely due to a reduction in the 1/rev component.

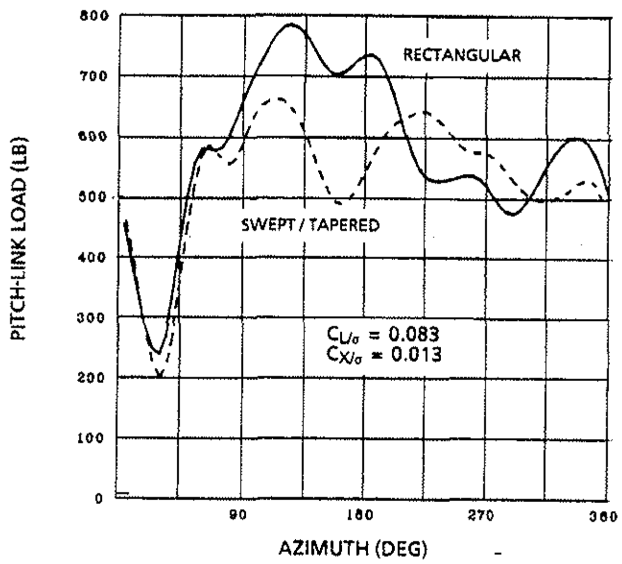
Blade Elastic Twist and Torsional Moment. Variations of mean and 1/rev elastic twist at 0.79R with airspeed are depicted in Fig. 11. Amplitudes of both the mean and 1/rev increased with airspeed. Reductions in both mean and 1/rev elastic twist at all airspeeds were predicted with the S/T tip blade. For example, at 180 kn, magnitudes of reduction were 0.42° in mean and 0.43° in 1/rev corresponding to 20% and 30% reductions respectively. The reduction in nose-down steady elastic twist directly resulted in lower collective requirement in rotorcraft trim. These reductions are further depicted in time history waveform in Fig. 12. A reduction in nose-down elastic twist was evident on the advancing blade. Hence, the benefit of the S/T tip on compressibility relief was clearly demonstrated.



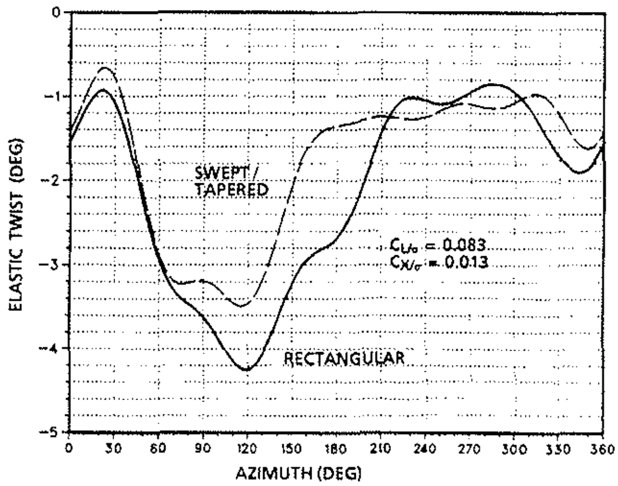
3H949
Fig. 8. Variation of oscillatory pitch-link load with airspeed



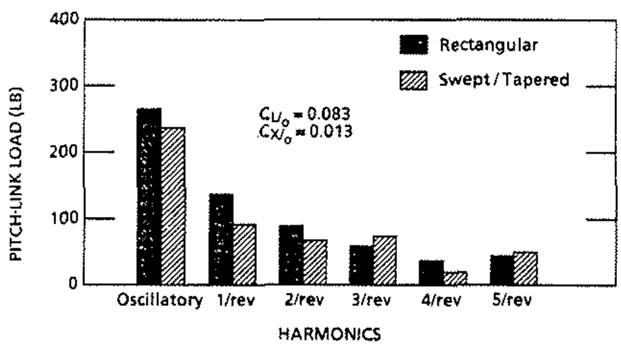
3H952
Fig. 11. Blade elastic twist at 0.79 R, GW = 8400 lb, 4000 ft/standard day



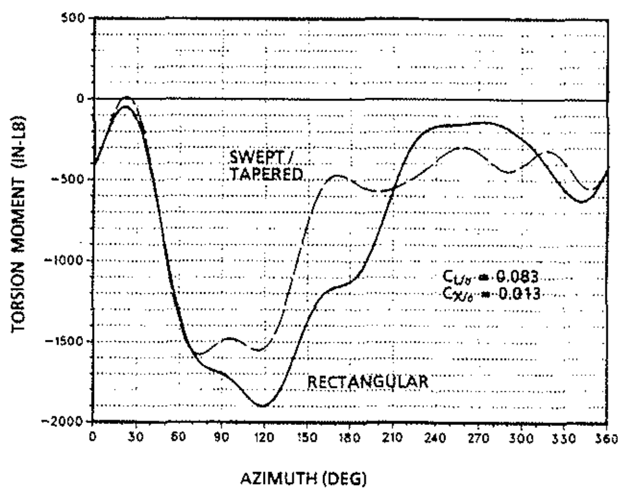
3H950
Fig. 9. Pitch-link load waveforms, V = 180 kn.



3H953
Fig. 12. Blade elastic twist at 0.79R, V = 180 knots.



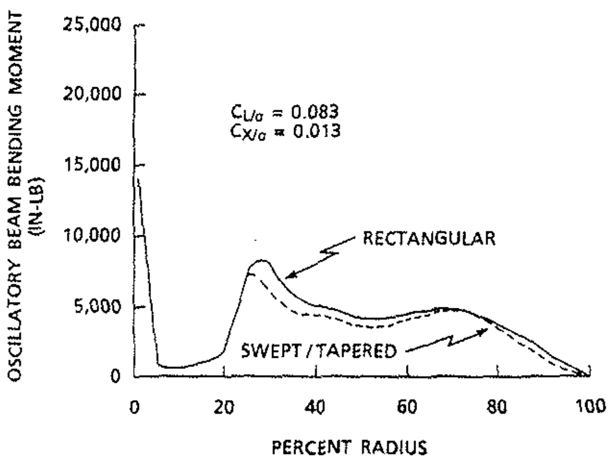
3H951
Fig.10. Harmonic decomposition of pitch-link loads, V = 180 knots.



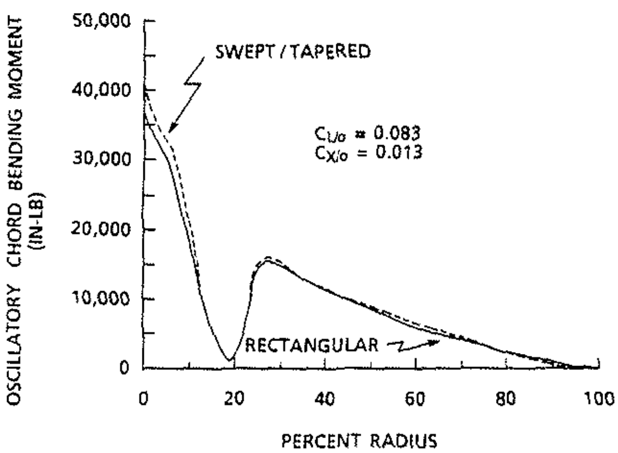
3H954
Fig. 13. Blade torsional moment at 0.79R, V = 180 knots.

Variations in blade torsional moment at 0.79R with azimuth at 180 kn are shown in Fig. 13. As expected, a reduction in torsional moment of approximately 10% was predicted.

Blade Loads. Computed blade beam and chord bending moments at 180 kn for the S/T and the rectangular tip blade are given in Figs. 14 and 15, respectively. A 10% reduction in the peak beam



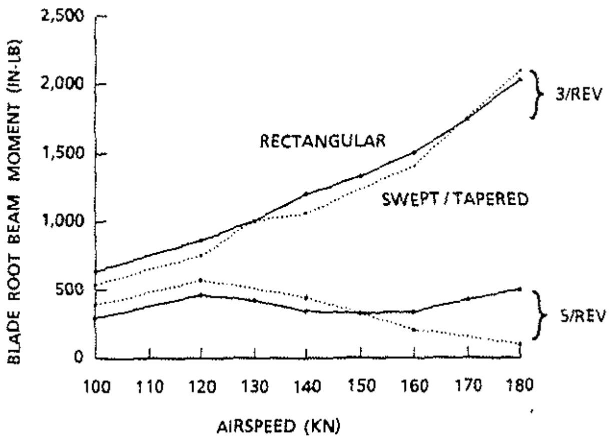
3H955
Fig. 14. Spanwise distribution of blade beam bending moment, V = 180 knots.



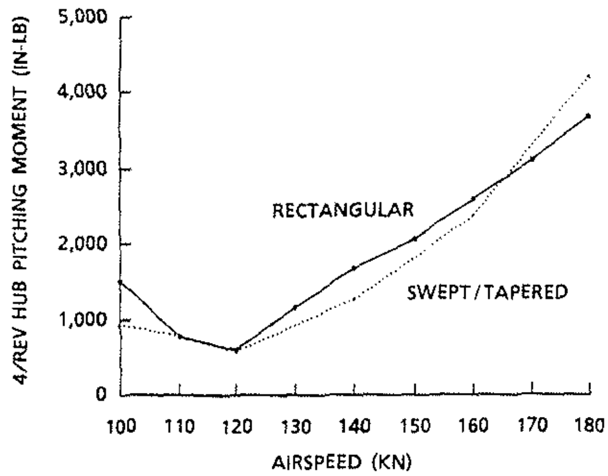
3H956
Fig. 15. Spanwise distribution of blade chord bending moment, V = 180 knots

bending moments due to the sweep/taper was shown. The effect of the sweep/taper on the chord bending moment was insignificant.

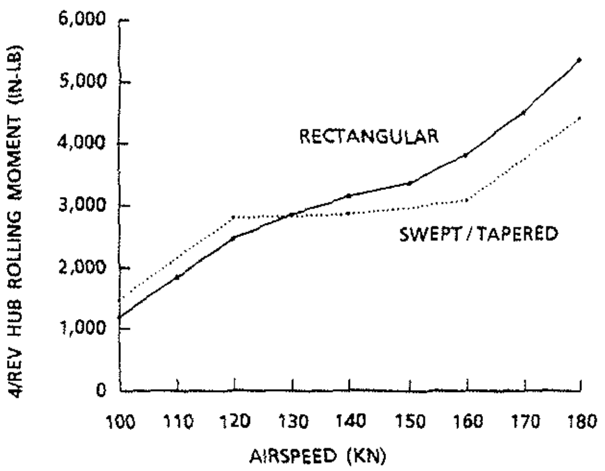
Vibration. The primary vibration source of a 4-bladed bearingless rotor in high speed is the 4/rev hub pitching and rolling moments. The major contributors to the hub moments are the blade root 3/rev and 5/rev beam bending moments. Variations of blade root 3/rev and 5/rev beam moments with airspeeds are shown in Fig. 16. The difference in 3/rev loads between the S/T blade and the rectangular blade was insignificant. A reduction in the 5/rev component at the high speed end was noted. Depending on the phase relationship between the 3/rev and the 5/rev components, variations of the 4/rev hub pitching and rolling moments with airspeed were computed and are shown in Figs. 17 and 18, respectively. Data indicate that a small reduction (approximately 5%) in the resultant hub moment was predicted with the S/T tip blade. When the resultant



3H957
Fig. 16. Variation of blade root 3/rev and 5/rev beam moments with airspeed, GW = 8400 lb, 4000 ft/standard day.



3H958
Fig. 17. Variation of 4/rev hub pitching moment with airspeed, GW = 8400 lb, 4000 ft / standard day



3H959
Fig. 18. Variation of 4/rev hub rolling moment with airspeed, GW = 8400 lb, 4000 ft / standard day.

hub moment was used as the indicator for the cabin vibration, the benefit of the tip sweep and taper on vibration was relatively small.

High-Speed Performance. Shaft horsepower requirements versus airspeed for the rectangular and the S/T tip blade are compared in Fig. 19. Results indicate that there was no benefit on power requirement with the sweep/taper throughout the airspeed range.

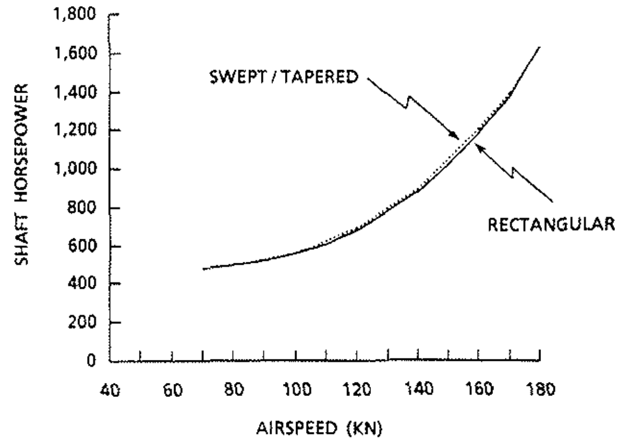


Fig. 19. Shaft horsepower requirement vs. airspeed, GW = 8400 lb, 4000 ft / standard day.

Variations of shaft horsepower versus rotor lift coefficient at two advance ratios are shown in Fig. 20. At $\mu = 0.30$ (132 kn), no appreciable difference in power was predicted throughout the rotor lift coefficient range studied. At $\mu = 0.363$ (160 kn), the benefit of the sweep/taper on power reduction was noted when C_L/σ was greater than 0.094. At $CL/\sigma = 0.106$, a power reduction of 3% was shown. The reduction was nearly all due to a reduction in profile power.

Swept/Tapered Tip, $\sigma = 0.0695$.

To identify the effect of solidity on loads, vibration, and performance, the baseline rectangular tip was replaced with the swept/tapered tip planform with no increase in the baseline blade chord length. This resulted in a thrust-weighted solidity of 0.0695. The rotor was dynamically tuned to closely match the natural frequencies of the rectangular tip blade. Computed performance, pitch-link loads, and 4/rev hub moments of this rotor were compared with those of the rectangular tip rotor and the matched solidity S/T tip rotor. The results are shown in Table 3. Data indicate that the lower solidity was beneficial for performance, loads, and vibration. In comparison with the baseline (rectangular tip) rotor, a 1% reduction in power, 20% reduction in pitch-link loads, and 10%reduction in vibration were possible with the 2.8% reduction in solidity.

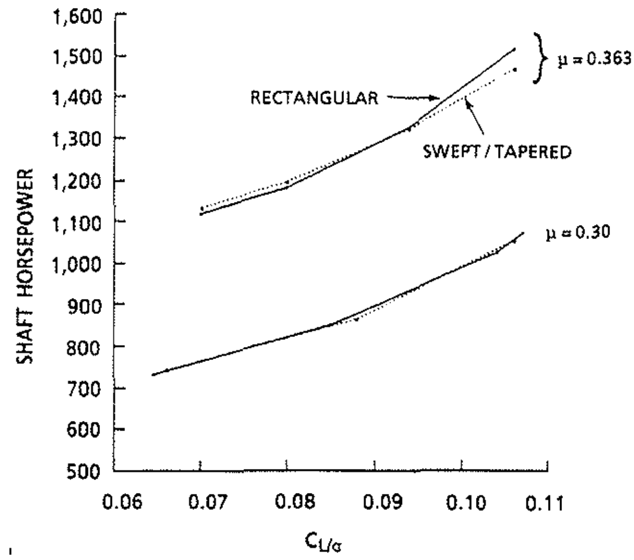


Fig. 20. Variation of shaft horsepower vs. rotor lift coefficient at two advance ratios.

Table 3. Effect of Solidity
GW = 8400 lb, V = 180 kn, 4000 ft/standard day

	Rectangular $\sigma = 0.0715$	Swept/ Tapered $\sigma = 0.0715$	Swept/ Tapered $\sigma = 0.0695$
Shaft horsepower	1630	1627	1608
Oscillatory pitch-link loads (lb)	265	236	203
4/rev hub pitching moment (in-lb)	3700	4200	3700
4/rev hub rolling moment (in-lb)	5328	4400	4200

Tip Airfoil Thickness.

As discussed earlier, the baseline rectangular tip as well as the swept/tapered tip had a 6% tip airfoil. The benefit of the combination of the thin tip with the sweep and taper on performance, loads, and vibration was not as great as that of the swept/tapered tip tested in the NASA Ames 40 by 80-ft wind tunnel (Ref. 8, 15, and 16). The tip airfoil reported in Ref. 8 was 9.5%. To examine the effect of tip airfoil thickness on the performance of the sweep/taper, the 6% tip airfoil used in our study was now changed to 10%. Results are tabulated in Table 4. Data indicate that, with the 10% tip airfoil, the sweep/taper reduced the power requirement by 3.8% and the pitch-link load by 15% while these

Table 4. Effect of Tip Airfoil
GW = 8400 lb, σ = 0.0715,
V = 180 kn, 4000 ft/standard day

	6% Tip Airfoil		10% Tip Airfoil	
	Rectangular	Swept/ Tapered	Rectangular	Swept/ Tapered
Shaft horsepower	1630	1627	1728	1663
Oscillatory pitch-link load (lb)	265	236	262	223
4/rev hub moments (in-lb)				
Pitching	3700	4200	3564	4164
Rolling	5328	4400	4908	4473

reductions were 0% and 10%, respectively, with the thin 6% tip airfoil. There was no significant difference on hub loads reduction between the 6% and the 10% airfoils.

Blade Torsional Stiffness

As mentioned earlier, the bearingless rotor selected for study in this paper was generic yet realistic and dynamically well tuned. The blade torsional stiffness was representative as evidenced by the proper placement of the torsion frequency (Fig. 7) and the reasonable blade elastic response (Figs. 11 and 12). A brief study was conducted on the effect of reduced torsion stiffness on blade elastic response and pitch-link loads. For this study, the blade torsion rigidity was reduced to 2/3 of the baseline value (a 1/3 reduction). Results are shown in Table 5. Data indicate that the magnitude of the blade elastic twist was doubled and both the steady and oscillatory pitch-link loads were increased.

Discussions

Results from the literature survey and the study conducted in this paper clearly indicate that the performance of the tip sweep/taper depends on many rotor design parameters. In addition to rotor solidity, tip airfoil thickness, and blade torsional stiffness, one of the other considerations is tip speed. During the development testing for M214ST (tip speed 781 ft/s) at Bell, the addition of the hyperbolic swept tip on the same diameter rotor resulted in an impressive increase in airspeed of 8 kn at sea level standard day and reduced hover power by 1.5%. The

Table 5. Effect of Blade Torsion Stiffness
GW = 8400 lb, σ = 0.0695,
V = 180 kn, 4000 ft/standard day

	Baseline Torsion Stiffness	67% Baseline Torsion Stiffness
Blade elastic twist at 0.79R (deg)		
Steady	-1.95	-3.78
1/rev	1.11	2.06
Pitch-link load (lb)		
Steady	565	709
Oscillatory	203	248

benefit however, may not be as great on a rotor with lower tip speed.

The benefit of the sweep/taper on aerodynamic performance has long been recognized. The benefit is derived from the compressibility relief due to the sweep and from the profile power reduction due to the chord tapering. Reductions in blade and control loads are usually realized when attentions are also given to rotor dynamics. It should be noted, however, that the sweep/taper would also increase the weight and cost. As discussed earlier (Table 1), a 5.4% increase in blade weight is identified. Bell currently uses various tip shapes on the following models: 214ST, 222U, OH–58C, and 206L. Based on experience at Bell, an additional 5% in blade manufacturing cost is estimated for a different tip planform.

Conclusions

From the study and discussions conducted in this paper, the following conclusions are drawn:

1. With a thin 6% tip airfoil, the benefit of the swept/tapered tip on forward flight performance is small. Up to 10% reduction in rotor loads and cabin vibrations is estimated with the S/T tip.

2. The penalties associated with the S/T tip are a 5.4% increase in blade weight and a 5% increase in blade manufacturing cost.

3. The performance of the sweep/taper planform depends on many design parameters, such as solidity, airfoil thickness, tip speed, rotor dynamics, and blade torsional stiffness. Therefore, it is imperative to integrate the tip shape in the overall design process.

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